Characterization of Spot Welding Behavior by Dynamic Electrical Parameter Monitoring

The use of two parameters—dynamic resistance and critical expulsion energy—is proposed for controlling resistance spot welding.

BY D. W. DICKINSON, J. E. FRANKLIN AND A. STANYA

ABSTRACT. A program was undertaken to develop techniques for studying the resistance spot welding process. A dynamic electrical parameter monitoring device was designed to simultaneously record the instantaneous values of voltage, current, power, and resistance during spot welding. The data obtained using this technique have been analyzed in terms of the relationships of these parameters to the phenomena occurring during the formation of a spot weld, to the effects of changes in welding variables on electrical parameters, and to the effects of variations in steel composition and properties.

The phenomena occurring during spot weld formation (surface breakdown, asperity collapse, heating of the workpieces, molten nugget formation, nugget growth, and mechanical collapse) can be understood through analysis of dynamic resistance curves. If expulsion occurs during a spot weld, it also is readily detected from this parameter. A generalized resistance curve consists of an initial very rapid drop in resistance to a minimum value within the first few cycles of current flow. This is followed by a rise to a maximum and finally a gradual decrease.

Dynamic resistance measurements can be used in obtaining a better understanding of lobe curves. The shape of the dynamic resistance curve for welds near the lobe boundary is correlated to the observed characteristics of these welds. The effects of changes in welding current and electrode force can also be related to the dynamic resistance curves. Spot weldability varies as a function of steel chemistry, and an improved understanding of these material effects is obtained by comparing dynamic resistance curves for various high-strength steels.

Expulsion is analyzed in terms of power curves integrated to obtain total weld energy input. It was found that expulsion occurs when the total useful energy into the weld exceeds a critical value. It is proposed that these two parameters, dynamic resistance and critical expulsion energy, can be used to control the spot welding process.

Introduction

It has long been known that the process of spot welding occurs through the localized melting and coalescence of a small volume of material due to the heating caused by the passage of electric current. This heating is equivalent to the product of the current squared times the total resistance of the material to be spot welded. During the process of spot welding, however, both the current and the resistance continually change as the material is heated and melts.

Until recently, spot weld characteristics have been determined by measurement of the initial or static resistance and the initial current surge at the onset of welding, or an average RMS current value obtained during welding. Recent papers have indicated that in order to fully characterize the spot welding process, a continuous or dynamic monitoring system is needed. This system would monitor and record instantaneous changes in the electrical functions during welding.

Several authors report continuous variations in the electrical parameters during welding of mild steel sheet to be typified by the sketches presented in Fig. 1. After approximately the first cycle, an increase in voltage across the welding electrodes and a decrease in current flowing through the weld zone occurs until a “peak region” is reached. Throughout the remaining portion of the weld cycle, the voltage decreases to a constant value while the current increases to a constant value.

These changes in voltage and current can also be represented as instantaneous or dynamic resistance. Several authors have calculated the dynamic resistance changes throughout the welding cycle by dividing the instantaneous voltage by the instantaneous current (\(R = E/I\)). This dynamic resistance trace is also plotted in Fig. 1. After an initial drop, it too rises to a peak in the first portion of the weld cycle, dropping off later in the cycle.

The appearance of this dynamic resistance trace and hence the basic welding mechanisms can be altered by changes in welding variables such as weld time, electrode force, and overall weld current. Bhattacharya and Andrews have made the following observations:

1. With low current values, the resistance trace does not show a prominent peak; with increased welding current, however, a well-defined peak appears.
2. With higher current values, the maximum or peak resistance occurs...
earlier during a weld.

3. For welds produced with high currents, the resistance trace indicates a lower value of resistance towards the completion of weld time.

4. A splash weld (expulsion), caused by excessive welding current, is characterized by a sudden step in the resistance trace.

Savage  has attempted to explain the shape of the resistance curve on theoretical grounds. When analyzing the resistance after each half cycle of current, he noted rectification which is believed to indicate the presence of oxide films for times as long as 6 to 8 cycles on some welds. He has also attributed the rise in resistance after the initial few cycles to be the result of the material heating. The latter decrease in resistance appears to coincide with the growth of the fused zone. The sudden drop in resistance upon expulsion was attributed to the increase effective contact area provided by the expelled metal trapped between the sheets.

These observations lay a pathway for effective utilization of dynamic electrical measurements in monitoring and control of spot welding. However, before such control can be utilized, a characterization of these electrical measurements throughout the entire range of acceptable spot weld parameters must be made.

One method for determining the range over which acceptable spot welds are obtained on plain carbon sheet is through the use of spot weld lobe curves. A typical spot weld lobe curve is presented in Fig. 2. A lobe curve is a graphical representation of ranges of welding variables over which acceptable spot welds are formed on a specific material welded with a preselected electrode force. The lobe curve is determined by making spot welds using different weld time/weld current combinations. Welds made with currents and/or times exceeding the upper curve experience expulsion on welding and are, therefore, considered unacceptable. Welds made with currents or times below the lower curve have insufficient size nuggets or exhibit brittleness during tearing and are likewise considered unacceptable. Only welds made with weld currents and times lying within the lobe area are acceptable.

Once the lobe curve is known, characterization of the dynamic electrical measurement can be made at critical areas on the curve. Such critical areas are a) around the lower limit line, b) at expulsion, and c) within the acceptable region.

Investigation Procedure

Objective

The objectives of this investigation were to:

1. Build a spot weld monitoring system capable of measuring dynamic values of voltage, current, resistance, and power.
2. Relate the phenomena occurring during spot weld formation to the changes in these basic electrical measurements thus confirming earlier speculations and developing new insight.
3. Characterize the dynamic electrical measurements over the range of weld parameters giving acceptable spot welds (i.e., over the lobe curve area) as a first step to using these electrical measurements for control of the spot welding process.

Materials

The spot weldability of several heats of plain carbon and high strength hot rolled and cold rolled steels was investigated. Specific chemical compositions of the materials for this investigation are listed in Table 1. These include plain carbon, rimmed, renitrogenized, Cb-added, Cb + V-added and Cb + Mn-added steels. Also, some welds were made on a Type 304 stainless steel.

Except where specifically noted, most of the data discussed are related to the welding of a 0.032 in. (0.8 mm) thick plain carbon aluminum-killed material (material A in Table 1).

Equipment

All welding was performed on two Taylor-Winfield air-operated electric resistance spot welding machines. These are equipped with Weldtronic controllers for electronic phase control (heat adjustment) and Duffers current analyzers for simultaneous measurements of weld time and secondary RMS weld currents. Electrode forces were accurately set at the recommended force for the sheet thickness being welded and checked several times throughout the welding program using a universal force gauge.

Electronic Circuits for Monitoring the Dynamic Electrical Parameters

A schematic of the circuits used to develop the welding parameters is shown in Fig. 3.

The instantaneous voltage across the electrodes is sensed by probes attached to the electrode holders.

Table 1—Chemical Analyses, %

| Material Type | Nominal gage, in. | C | Mn | Si | S | P | Cu | Ni | Cr | Cb | V | Al | O | N |
|---------------|------------------|---|----|----|--|--|---|---|---|----|---|---|---|---|---|
| A Plain C, AK  | 0.032            | .07 | .34 | .01 | .020 | <.008 | .01 | .02 | <.01 | <.01 | <.01 | .05 | .006 | .007 |
| B Renitrogenized | 0.032           | .11 | .66 | .01 | .040 | .009 | .02 | .02 | .02 | <.01 | <.01 | .01 | .032 | .022 |
| C High Cb, low Mn | 0.032   | .04 | .37 | .01 | .027 | <.008 | .04 | .02 | .02 | .076 | <.01 | .044 | .004 | .006 |
| D Low Cb, high Mn | 0.032 | .081 | .90 | .01 | .018 | <.008 | .03 | .01 | .01 | .028 | <.01 | .022 | .003 | .006 |
| E High Cb, high Mn | 0.032 | .069 | .92 | .015 | .017 | <.008 | .03 | .01 | .01 | .072 | <.01 | .039 | .003 | .003 |
| F Plain C | 0.053 | .075 | .39 | <.01 | .017 | <.008 | .03 | .03 | .02 | <.01 | <.01 | .008 | — | — |
| G CB-V | 0.056 | .087 | 1.40 | .54 | .011 | <.008 | .04 | .03 | .15 | .08 | .017 | — | — | — |
| H 0.34 stainless | 0.053 | .092 | 1.40 | .60 | .014 | <.01 | .35 | 7.6 | 17.8 | <.01 | <.01 | <.01 | — | — |

* Mn = 0.35, Cu = 0.12.
Probes in this location sense the entire voltage drop attributed to the electrodes and the work pieces. Other workers have attached probes at different locations, such as the sheets being welded; however, probes permanently mounted to the electrodes or electrode holder are more durable and perform over long weld campaigns. The sensed voltage is amplified for proper scaling. The amplified voltage signal is then simultaneously sent to a switch (SW1) and an analog computing module which converts the instantaneous voltage into a signal that is proportional to the root-mean-square or effective voltage. The output of the voltage RMS module is then sent to SW1, an analog divider module input, and a recorder channel.

The instantaneous current is sensed by a Hall-Effect device, amplified for proper scaling and sent to SW1 and the input of an analog RMS module which converts the instantaneous signal into a signal that is proportional to the effective or heating value of the welding current. The RMS current signal is then sent to SW1, the input of an analog divider module and a recorder channel.

When SW1 is in position 1, the instantaneous voltage and current signals are connected to an analog multiplier module whose output is proportional to the product of the instantaneous voltage and current which is the instantaneous power dissipated across the welding electrode. When SW1 is in position 2, the outputs of the voltage and current modules are connected to the inputs of the multiplier and the output signal is the product of the effective voltage times the effective current. The product of the instantaneous voltage and current is equal to the product of the effective voltage and current when voltage and current are in time synchronization (in phase"). The output of the multiplier is sent to a channel of the recorder.

The signals from the current and voltage RMS modules are also connected to the inputs of an analog divider module. This module divides the voltage signal by the current signal and develops a new signal which is proportional to the changing resistance (dynamic resistance) between the electrodes during the welding cycle. This signal is then sent to a recorder channel.

The high speed strip chart recorder can then simultaneously record the effective welding current, effective voltage across the welding electrode, power dissipated during the welding cycle, and the changing resistance between the electrodes during the welding cycle.

Dynamic Electrical Measurement

Dynamic Resistance Measurements around Lower Lobe Boundary

As a means of characterizing the dynamic electrical parameters in relation to the spot weldability lobe curve, several welds were made with a weld current held constant (at approximately 8000 A) and varying weld time from 2 to 12 cycles. A full complement of dynamic electrical measurements was made. This allowed the characterization of electrical parameters around the lower lobe boundary (insufficient nugget size line) of the lobe curve presented in Fig. 4.

**Fig. 4—Lobe curve for plain carbon AK steel (0.032 in., i.e., 0.81 mm)**

**Fig. 5—Dynamic resistance curves around lower lobe boundary**
The electrical parameter proving the most useful was the dynamic resistance. Figure 5 shows the dynamic resistance curves determined along with metallographic cross-sections of the respective welds. The curves presented throughout are those obtained by connecting the peak points of the dynamic resistance for each half cycle of weld time.

The weld made for two cycles showed evidence of heating, but no melting was seen on the weld cross section. The dynamic resistance curve dropped from its initial high value to a minimum and just started to increase again at the termination of the two cycle weld time. On the four cycle weld some melting was noted. This was accompanied by further development of the dynamic resistance curve. The resistance showed a substantial increase after passing through the minimum point.

The six cycle weld developed a nugget diameter approximately equal to the minimum acceptable diameter and, therefore, fell close to the lower limit of the lobe curve. The resistance curve for this weld was fully developed with weld termination near the peak in the curve. The weld made at twelve cycles fell well within the acceptable region of the lobe curve. The weld nugget was fully developed and the dynamic resistance curve exhibited the full characteristic shape as observed by others.

Interpretation of Dynamic Resistance Curves

Based on the above analysis and upon similar analyses of other authors, the following interpretation for the typical shape of the dynamic resistance curves is given. With reference to Fig. 6, the stages of spot weld formation can be described as follows:

Stage I. The work pieces are brought into contact under the pressure provided by the electrode force. This creates areas of electrical contact at the points where asperities on the surfaces meet. Voltage is applied between the electrodes causing current to flow at the microcontact points. The resistance between electrodes at this point is equal to the sum of the bulk resistance of the two work pieces, the two electrode-to-work contact resistances, and the work-to-work contact resistance.

Under normal conditions, surface films, oxide layers, or other contaminants will be present on the work pieces. Since these are essentially insulators, the initial contact resistance will be very high. Therefore, the initial generation of heat will be concentrated at the surfaces, especially at the work-to-work contacts. This heat will cause the surface contaminants to break down, resulting in a very sharp drop in resistance.

Stage II. Immediately after the breakdown of surface contaminants, metal-to-metal contact exists. However, the surface resistance may still remain relatively high due to the limited area for current flow provided by the asperity contacts. Heating then is concentrated at the work-to-work surface, and temperature in this region and in the bulk material will increase. As heating progresses, the asperities soften and the contact area increases thus causing resistance to decrease. At the same time, increasing temperature results in increasing resistivity, thus providing an opposite effect. The competition between these two mechanisms determines whether resistance is increasing or decreasing and thus determines the position of the minimum. Eventually, the increase in contact area will be overcome by the increasing temperature effect, and the total resistance will begin to rise.

Stage III. During this period, the increase in resistivity resulting from increasing temperature dominates the resistance curve. The end of Stage III should correspond to local melting beginning to occur at the asperity contacts. The transition to Stage IV will probably occur near the inflection point in the curve. (dR/dt = 0).

Stage IV. Three mechanisms influence Stage IV. The bulk of the work pieces continue to increase in temperature, thus causing resistivity and resistance to increase. But, the heat being generated also causes additional melting to occur at the surfaces, increasing the size of the molten region and the cross-sectional area available for current flow. This mechanism causes a resistance decrease. Also, increased softening will result in some mechanical collapse, shortening the path for current flow and decreasing resistance. The peak is a consequence of the temperature beginning to stabilize, while nugget growth and mechanical collapse begin to dominate, and therefore resistance starts to decrease.

Stage V. Beyond the peak, the growth of the molten nugget and mechanical collapse continue to cause resistance to decrease. If the nugget grows to a size such that it can no longer be contained by the surrounding solid metal under the compressive electrode force, expulsion will occur.

This series of events, Stages I through V, offers a consistent interpretation of the shape of the dynamic resistance curves observed for spot welds made in the plain carbon AK material. Variables expected to cause significant variation in the shape include current level, electrode force, and material being welded. These factors are considered below.

Effect of Current Level on Dynamic Resistance Curve

In order to examine the effect of
varying current level upon the shape of the dynamic resistance curve, a number of welds were made in the 0.032 (0.81 mm) plain carbon AK steel at 12 cycle weld time with varying current levels. The current levels investigated were:

1. Those that fell just below the acceptable lobe region, where molten nuggets were formed but were of insufficient size.
2. Those that fell within the acceptable region of the lobe curve.
3. Those experiencing expulsion.

Thus, a full range of current levels were studied. The results are presented in Fig. 7.

At low currents, when an undersize or brittle nugget forms, the curves show a distinct initial resistance spike which decays within the first two cycles. At currents near the middle of the acceptable welding range, the initial spike is still present but the decay is more rapid. At expulsion level currents the decay is so rapid that the initial spike is barely detected. Since the resistance spike is believed to be a result of the breakdown of surface films and the collapse of asperities during the initial stages of the welding pulse, the time required for it to decay will depend on the rate at which heat is supplied to the weld, i.e., the power ($E \times I$). Therefore, at low currents a measurable amount of time is required for sufficient heat to be supplied; hence, a distinct decaying spike is detected. At high currents, surface film breakdown and asperity collapse are so rapid that the instrument is not capable of recording the initial spike. In this case, Region I of the curve in Fig. 6 is just barely observed and the $\beta$ minimum is reached almost immediately after current begins to flow.

With regard to the $\beta$ maximum, Batycharya and Andrews' indicate that this is the point at which melting of sheet-to-sheet contacts first occurs. They also propose that the decreasing slope of the curve near $\beta$ is a result of partial collapse of the sheet-to-sheet interface brought about by softening. The present work indicates that melting occurs prior to the $\beta$ peak and that the peak itself merely signifies the point at which resistance drop due to molten nugget growth and mechanical collapse overcomes the resistance rise resulting from increasing temperature. Figure 5 supports the hypothesis that melting occurs prior to the $\beta$ peak. The $\beta$ peak in Fig. 5 occurs at about 6 cycles, but this Fig. 5 shows that a substantial amount of melting has occurred after only 4 cycles. No melting occurred up to 2 cycles.

Therefore, because the $\beta$ peak is a balance point between a resistance increase and a resistance drop, the position of the $\beta$ peak must be dependent upon heating rate (i.e., current level). At very high currents (expulsion level), the $\beta$ peak is reached early in the welding pulse (after 4-5 cycles in Fig. 7). In the middle current range $\beta$ is reached after 5-6 cycles. At low currents, 7 or more cycles pass before the maximum. This behavior indicates that at lower currents heating rate is slower; therefore, more time is required for nugget growth and mechanical collapse to occur. Since heating is proportional to power input ($P = ER$), faster rates of heating and shorter times to reach $\beta$ should be associated with higher current levels or higher resistance.

**Effect of Electrode Force on Dynamic Resistance Curve**

In order to examine the effect of electrode force on the shape of the dynamic resistance curve, spot welds were made in the 0.032 in. (0.81 mm) plain carbon AK material with electrode forces varying from 350 to 1500 lb (159 to 680 kg). The dynamic resistance traces obtained from three of these welds are presented in Fig. 8.

As the force was increased, the curve flattened such that the maximum resistance decreased and $\beta$ was shifted to later times in the welding pulse. Also, as the force increased, there was a general decrease in the resistance level. Since all the welds were made at identical tap and heat control settings, which resulted in similar current levels (6200-6700 A Duffers current), decreasing resistance results in a decrease in the rate at which energy is supplied to the weld ($P = ER$). Thus, the $\beta$ peak is shifted to longer times, and nugget formation is delayed as electrode force is increased.

Lower electrode forces, therefore, should favor nugget formation. This hypothesis is confirmed by the results of nugget pullout tests on the welds represented in Fig. 8. Ductile nugget pullout occurred only at the lowest electrode forces. At higher forces, nuggets were brittle, and at the highest electrode forces no nugget was formed. This confirms earlier work which indicated that higher electrode forces tended to move the lobe curve to the right.

**Effect of Material on Dynamic Resistance Curve**

The material variable may include not only the composition of the steels, but also the surface condition. Surface effects have been studied and have been found to have noticeable effects on spot weldability. Likewise, chemistry variations have also been found to have noticeable effects on spot weldability.

To demonstrate the effect of material on the shape of the dynamic resistance curve, full lobe curves (not presented herein) were determined for materials A through E (Table 1). Using the lobe curves as a baseline, dynamic resistance traces were determined for...
a range of nugget conditions from undersize nugget to expulsion at 12 cycle weld current, exactly as indicated for material A in Fig. 7.

The dynamic resistance curves obtained at three different secondary RMS current levels for all five materials are compared in Fig. 9. For each weld, the appearance of the nugget is also indicated. Comparisons between the five steels represented in Fig. 9 can be made by considering:

1. The shape of the dynamic resistance curves associated with acceptable welds.

2. Shape differences associated with acceptable welds in different materials.

The general shape of the dynamic resistance curve as proposed earlier, consisting of an initial spike which decays rapidly followed by a secondary $\beta$ peak, is observed for all five materials. It is clear that the curves associated with acceptable welds in all materials exhibit a pronounced $\beta$ peak. Undersized welds resulted when the weld cycle was terminated before or just slightly after reaching the $\beta$ peak. This is probably the result of an early surface breakdown for this material. In all cases, however, the higher alloyed materials exhibit a pronounced $\beta$ peak of earlier weld times. Thus, the evaluation of the effect of variation in material chemistry and surface condition is possible by means of analyzing the dynamic resistance curves.

Analysis of Dynamic Electrical Parameters at Expulsion

As indicated earlier in Fig. 1, the expulsion point on the dynamic resistance curve is noted by a sharp drop in electrical resistance. This drop in resistance is probably the result of mechanical collapse around the nugget reducing the thickness of material through which additional current must flow together with the increased effective contact area provided by the expelled metal trapped between the sheets.

In order to obtain additional insight into the criteria for expulsion, the dynamic electrical parameters were measured. Values of instantaneous power were recorded for a series of spot welds and the energy input was determined by measuring the area under the power vs. time curve. During the course of this investigation, it became apparent that the best data were obtained on the welds with the longer weld times. For this reason, thicker plain carbon sheet (0.053 in., or 1.3 mm), material F, was selected so the 15 cycle weld times could be used. Welds were made with two different transformer tap settings and heat settings (percent of full sine wave) ranging from 60 to 100%.

The results obtained from the power and energy determinations are presented in Fig. 10. Here, the total weld energy input is plotted as a function of the heat control setting (percent full sine wave) up to the expulsion point. Thereafter, for higher heat control settings, both the total energy into the spot weld as well as the energy into the weld until expulsion occurred is plotted.

It is clear from these data that acceptable weld nuggets are obtained, irrespective of transformer tap setting or heat control setting, up to a critical energy. It is speculated that the onset of expulsion in steels can be related to the critical energy input. At that point, a balance between energy input by FR heating and energy out by conduction, convection or radiation is no longer maintained. The molten nugget growth occurs uncontrolled thus resulting in expulsion. This being the case, the critical expulsion energy should be a function of material parameters such as electrical resistivity and thermal conductivity.

Materials with high electrical resistivity and lower thermal conductivity will tend to develop the unstable condition at lower energy input value. As a means of confirming this, critical expulsion energy values were determined for a Cb-V material (material G) and a Type 304 stainless steel (material H). The results presented in Fig. 11...
clearly show the effect of the higher resistivity-lower conductivity materials.

Use of Dynamic Electrical Parameters for Control of Spot Welding

Throughout the work described herein, correlations have been made between the dynamic electrical parameter observations for spot welds and the location of those spot welds relative to the acceptable weld lobe region. For welds exhibiting undersized nuggets (i.e., for welds made with weld parameters below the acceptable lobe range), the dynamic resistance curve does not show an obvious β peak. Acceptable welds are those which have welding parameters set such that an obvious β peak in the dynamic resistance curve is obtained, but also such that the critical expulsion energy input is not reached. Thus, the lower and upper boundary on acceptable spot welds is known.

Equipment which can monitor the dynamic parameters, compare the values with preset values, and then control the spot weld heat control and/or weld time to maintain the parameters within the boundary limits will control the spot welding process.

Conclusions

1. A dynamic electrical monitor system was built which allowed the continuous monitoring of voltage, current, resistance, and power during the spot welding process.
2. The shape of the dynamic resistance curve was related to the phenomena occurring during spot welding. The occurrence of the predominant β peak signified the production of an acceptable size nugget.
3. Variations in the shape of the dynamic resistance curve were related to variations in material, secondary RMS current, and electrode force.
4. A critical energy level for expulsion was observed.
5. Using information established for dynamic resistance and critical expulsion energy, a spot weld control mechanism was proposed.

References